

The University of Chicago

THE DISTANCES OF THE REDDENED B STARS

A DISSERTATION SUBMITTED TO THE FACULTY
OF THE DIVISION OF THE PHYSICAL SCIENCES
IN CANDIDACY FOR THE DEGREE OF DOCTOR
OF PHILOSOPHY

DEPARTMENT OF ASTRONOMY AND ASTROPHYSICS

1941

By

JOHN A. O'KEEFE

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ABSTRACT

The spectral types and luminosities of 179 heavily reddened B stars have been estimated on low-dispersion slit spectrograms. Excluding the reddened Be stars, which may be reddened by intrinsic causes, the reddening of the B stars is attributed to a very patchy layer of absorbing matter. The coefficient of absorption is found to vary rapidly and to reach its highest values in the obvious dark areas. By using the reddened B stars, the distances of the largest dark nebulae are estimated, and the results are compared with the star counts. The agreement is good for the more distant dark nebulae and poor for the nearer ones. This is interpreted as confirmation of the connection of the reddened B stars with the dark nebulae.

I. THE OBSERVATIONS

In several recent papers¹ Stebbins, Huffer, and Whitford have discussed the selective absorption in the Galaxy as measured by the colors of the B stars which they have observed. They find a large range in the color excesses of their B stars even when these are comparatively near one another and at the same estimated distance. In the fourth of these papers they suggest two possible explanations: (1) that the heavily reddened stars are c stars or other highly luminous stars; (2) that the absorption is spotty and that the more heavily reddened stars lie in regions of great obscuration. A third possible explanation, which they do not mention, is that a part of the reddening of the B stars is due to intrinsic causes. The present paper is an attempt to find out, by a spectroscopic examination of the heavily reddened B stars, to what extent each of these causes contributes to the observed irregularity.

The material and the methods of observation.—The material consists of spectrograms of 179 B and A stars chosen from the catalogue by Stebbins, Huffer, and Whitford of 1332 B stars.² In the northern hemisphere, spectra have been obtained for nearly all such stars; in the southern hemisphere nearly all stars down to 9.0 mag. have been photographed. The first catalogue of 733 stars is nearly complete from O to B5, brighter than 7.5 mag. and north of $\delta = -15^\circ$; and the catalogue of 1332 B stars is nearly complete from O to B2, to -40° and to the limit of the *Henry Draper Catalogue*. The material discussed here includes, therefore, most of the reddened B and A stars within these limits and brighter than 9.0 mag. in the southern hemisphere. It does not include stars which they list as O's.

These stars have been classified and their luminosities determined on low-dispersion slit spectrograms. The majority of the stars in the northern hemisphere were photographed at the Yerkes Observatory with a dispersion of 110 Å/mm at $H\gamma$. For the southern stars, as well as for some faint northern stars, the Cassegrain spectrograph of the McDonald Observatory was used, giving a dispersion of 76 Å/mm at $H\gamma$. Comparison stars taken with the same instrument were obtained for both sets of spectrograms. At first, the 40-inch telescope was diaphragmed for the brighter stars; but since this amounted to diaphragming the spectrograph, this practice was discontinued, for fear of systematic differences in definition between the brighter and fainter stars. Agfa Super-Pan Press films and Cramer Hi-Speed Special plates were used. The scale of spectral types and absolute magnitude was that of Williams and Edwards.³ However, it was impossible

¹ Joel Stebbins and C. M. Huffer, *Pub. Washburn Obs.*, **15**, 217, 1934; Joel Stebbins, C. M. Huffer, and A. E. Whitford, *Ap. J.*, **90**, 209, 1939; **91**, 20, 1940; **92**, 193, 1940.

² *Op. cit.*, **91**, 20, 1940.

³ E. G. Williams, *Ap. J.*, **83**, 305, 1936; E. G. Williams and D. L. Edwards, *M.N.*, **98**, 467, 1938.

to use Williams' criteria of spectral type. The lines of ionized elements upon which he depends were usually too faint on the dispersion used to permit accurate estimates of the intensities. From the standard stars, therefore, another set of criteria was devised (Table 1).

No attempt was made to assign luminosities to normal Be stars or to stars whose diffuse H absorption lines suggested a state of incipient emission. On the other hand, a group of stars having narrow lines and having emission at $H\alpha$ and sometimes at $H\beta$ were considered to be fundamentally different and were classified with the normal stars. The distinction between these stars is perfectly clear in η and χ Persei, for example, where a few of the very brightest stars have $H\alpha$ in emission; and many stars around the tenth magnitude are typical Be's. The distinction is usually easy to make observationally, since the lines of normal Be stars are extremely broad and shallow.

The criteria used for spectral type are somewhat sensitive to luminosity, and vice versa. It was therefore necessary to classify at the same time for spectral type and for luminosity. The procedure was to estimate the type roughly, using all visible lines; then to determine the luminosity by comparison with standard stars of the same rough type; and finally to determine the type by comparison with stars of the same luminosity.

TABLE 1
CRITERIA OF SPECTRAL TYPE AND LUMINOSITY

Type	Criterion of Type	Criterion of Luminosity
O	$He\ II/He\ I$	.....
B0	$O\ II, Si\ IV, C\ III$	$He\ I$
B1, B2	$O\ II, Si\ IV$	H
B3-B8	$He\ I$	H
B8-A2	$He\ I/Si\ II, Si\ II/Fe\ II$	H

In this work it was considered sufficient to estimate the difference in the intensities of the lines under an eyepiece. Williams and Edwards remark that on their dispersion (about twice that used here) it was "barely possible" to detect the difference in intensities of the H lines between the main-sequence star ι Herculis and the giant 67 Ophiuchi. With the dispersion used in this investigation, the difference was quite striking and could be subdivided into at least three or four steps. This result is probably due to the smearing-out of the line core by the lower resolving-power of the spectrograph, as well as to the crowding-together of the wings of the lines.

It was found that the apparent intensity of the H lines was decreased on overexposed spectrograms and increased on those underexposed. In order to allow for this, deliberately overexposed and underexposed spectra were obtained for the standard stars.

Comparison with other observers.—A comparison of the types of this list with those of the Victoria catalogue of radial velocities⁴ gives, for 58 stars, a probable error of ± 1.1 spectral subtypes and a systematic difference, Victoria minus O'Keefe, of $+0.4$. For the same group of stars the probable error derived from a comparison with the Harvard types is ± 1.7 , with a negligible systematic difference. The rather large accidental errors are due in part to the difficulty of classifying the Be and c stars which make up such a large fraction of the reddened B stars. For example, for 875 stars in the Victoria catalogue of radial velocities the probable error from comparison with the Harvard classes is ± 0.9 spectral subtypes; but for 58 reddened B stars this becomes ± 1.3 .

For the later B stars there is a systematic difference between the Harvard classifica-

⁴ J. S. Plaskett and J. A. Pearce, *Pub. Dom. Ap. Obs.*, 5, 99, 1931.

tion and both the Victoria classification and the present list, in the sense that late B and A supergiants tend to be classified earlier at Harvard. This is undoubtedly due to the use, by the Harvard observers, of the H lines as criteria of spectral type. The supergiants resemble the early B stars in the weakness of their H lines.

A. D. Thackeray and H. E. Butler⁵ give a method for finding the true dispersion of a set of spectral types from a comparison of three catalogues, on the assumption that there is no correlation of the systematic errors. A solution by this method, using the Draper and the Victoria catalogues, gives a probable error of ± 1.1 spectral subtypes for the types of the present paper. This is by no means an accurate estimate, since the condition of independence of the residuals is certainly not satisfied. Nevertheless, we may conclude that the probable error of the present types is of the order of ± 1 spectral subtype.

The normal colors of the stars used in this paper are those given by Stebbins and Huffer.⁶ Since the differences in normal color from one subclass to the next between B0 and A2 average 0.014 mag., the above value of the probable error of a type implies

TABLE 2
STARS IN η AND χ PERSEI

Star	Vis. Mag.	Spec. Type	Obs. Color	Color Excess	Abs. Mag.	Distance Modulus
13716.....	8.4	B1	-0.06	+0.15	-3.5	10.8
13745.....	7.96	B0	- .09	.13	4.5	11.6
13841.....	7.21	B2	- .07	.13	5.0	11.3
13854.....	6.42	B1	- .04	.17	5.7	10.9
13970.....	8.5	B1	- .07	.14	4.0	11.5
14053.....	8.3	B1	- .07	.14	3.5	10.8
14134.....	6.66	B1+	+ .03	.24	4.0	9.0
14143.....	6.66	B1+	+ .06	.27	5.8	10.6
14322.....	6.84	B8	.00	.13	5.8	11.7
14542.....	6.95	B3	+ .17	.36	4.3	8.7
14818.....	6.24	B2+	+ .06	.26	5.7	10.1
14956.....	7.32	B1+	+0.16	+0.37	-5.8	10.5

a probable error in the estimated true color of ± 0.015 mag. The errors of the measured colors are estimated by Stebbins, Huffer, and Whitford⁷ as ± 0.01 to ± 0.02 for colors measured at Mount Wilson and ± 0.02 to ± 0.03 for colors measured at Madison. Thus, the contribution of the errors of classification to the error of the color excesses is approximately the same as that of the photoelectric colors. The accidental probable error of a color excess in the present paper is therefore ± 0.02 to ± 0.03 . There is a considerable possibility, as was pointed out by the photoelectric observers, that the normal colors are affected by systematic errors of somewhat larger size.

We may test the luminosities of the present work by comparing with the apparent magnitudes, corrected for absorption, of the stars in η and χ Persei. In Table 2 are given the results of this comparison for 12 stars in the cluster which are of type B, have radial velocities in the neighborhood of -40 km/sec, and have colors by Stebbins, Huffer, and Whitford. The radial velocities were published by van Maanen,⁸ who attributed these stars to the cluster on this ground. It is, however, immaterial for the present purpose whether the community of velocity is due to cluster motion or, as has been suggested, to galactic rotation. In either case we have a group of stars at roughly the same distance.

⁵ *M.N.*, 100, 450, 1940.

⁷ *Op. cit.*, 91, 25, 1940.

⁶ *Op. cit.*, p. 221.

⁸ *Mt. W. Contr.*, No. 205, 1920.

The absorption is assumed, in conformity with Stebbins, Huffer, and Whitford, to be seven times the color excess.

The mean value of the distance modulus is found to be 10.8 mag., corresponding to a distance of 1350 parsecs, or somewhat lower than the values determined in other ways. The probable deviation of an individual value is ± 0.61 mag.; this corresponds to a probable error of about 30 per cent in the distance.

Observational results.—A considerable number of stars of very high luminosity have been found in the course of the present work. Those not previously announced are given in Table 3. In addition to these stars, the majority of the heavily reddened B stars are

TABLE 3

HD	m_{vis}	Sp.	M	E
15785.....	8.41	B1	-5.6	+0.29
41398.....	7.45	B1	6.0	.19
164865.....	7.9	B8	5.6	.44
167838.....	6.64	B6	5.6	.24
170938.....	8.1	B1	5.7	.49
E227836.....	9.6	B5ea	-5.5	+0.19

more luminous than average main-sequence stars. Thus, out of the 130 stars whose absolute magnitudes are given in this paper, 56 are between -5.1 and -6.0, 30 are between -4.1 and -5.0, 29 between -3.1 and -4.0, 13 between -2.1 and -3.0, and 2 are fainter than -2.1. Two-thirds of these stars are brighter than -4.0.

The star HD 174571 was found to have *H α* bright; and the stars HD 173438 and 216411 were also suspected of having emission at *H α* .

Table 4 lists the stars studied in this paper. It is arranged in the same way as Table 2, except that the seventh column gives the computed distance in parsecs; an asterisk in the eighth column indicates a note at the end of the table. Since some of the plates used in the present investigation were not red-sensitive, it has been impossible to make an independent investigation of the emission in these stars. For this reason, in the third column the notation "e," "ea," etc., is taken from the catalogue of Stebbins, Huffer, and Whitford (who had access to Merrill's unpublished material), except in the case of the 3 stars mentioned above and of the stars HD 194839, HD 195592, and E227836, for which the notation was changed from "e" to "ea" to conform with Merrill's notation for stars of high luminosity.

For 3 double stars for which only the combined light is accurately known, the magnitude of the brighter component was computed from the difference of brightness in *Aitken's Catalogue of Double Stars*, and the distance modulus was obtained from the corrected magnitude.

TABLE 4

HD	Vis. Mag.	Spec. Type	Obs. Color	Color Excess	Abs. Mag.	Distance	Re- marks
1383.....	7.8	B0	-0.02	+0.20	-4.5	1500	
2789.....	8.3	B1:e	+ .05	.26			
3940.....	7.40	A2	+ .23	.28	5.5	1500	
4717.....	8.2	B9	+ .18	.30	3.5	850	
4768.....	7.9	B5	+ .06	.23	2.5	550	
4841.....	7.06	B5	+ .14	.31	6.0	1500	
5551.....	7.7	B1	+ .13	.34	4.5	900	
6182.....	8.4	B1	+ .07	.28	4.0	1200	
7103.....	8.4	B2	+ .15	.35	4.0	1000	
7902.....	7.2	B1:e	+ .03	.24	3.0	500	*
9105.....	7.46	B4:(e)	+ .16	.34	5.5	1300	
9311.....	7.26	B5	+ .07	.24	5.3	1500	
10808.....	7.4	B3+	- .01	.18	5.0	1700	
E232552.....	8.2	Boe	+ .01	.23			
12301.....	5.62	B6	+ .05	.21	5.7	950	
12953.....	5.90	A2	+ .06	.11	5.5	1300	
13476.....	6.50	A2	+ .16	.21	5.5	1300	
13744.....	7.8	A0	+ .20	.30	5.5	1700	
14010.....	7.05	A0	+ .10	.20	5.5	1700	
14134.....	6.66	B1+ea	+ .03	.24	4.0	650	
14143.....	6.66	B1+	+ .06	.27	5.8	1300	
14433.....	6.54	A1	+ .13	.20	5.5	1300	
14535.....	7.46	A1	+ .21	.28	5.5	1600	
14542.....	6.95	B3	+ .17	.36	4.3	550	
14818.....	6.24	B2+ea	+ .06	.26	5.7	1100	
14956.....	7.32	B1+	+ .16	.37	5.8	1300	*
15316.....	7.30	A1	+ .30	.37	5.5	1100	
15497.....	7.20	B5	+ .26	.43	5.8	1000	
15558.....	7.82	O7	+ .12	.35			
15570.....	8.0	O6	+ .20	.43			*
15571.....	8.0	B1	+ .02	.23	5.5	2400	
15690.....	7.7	B2	+ .18	.38	5.0	1000	
15785.....	8.41	B1	+ .08	.29	5.6	2500	
16243.....	8.4	B2+	+ .11	.31	4.5	1400	
16778.....	7.71	A2	+ .39	.44	5.5	1100	
17088.....	7.54	A0	+ .25	.35	5.5	1300	
17145.....	8.0	B5	+ .28	.45	5.5	1200	
17857.....	7.78	B8	+ .16	.29	5.7	2000	
18326.....	7.91	O8	+ .05	.28			
19243.....	6.54	Be	+ .06	.26			*
20017.....	7.90	B9e	+ .04	.16			
21212.....	8.3	Bo:e	+ .11	.33			
21389.....	4.76	A0:ea	+ .13	.23	5.5	550	*
21448.....	7.37	B1+	+ .04	.25	3.5	850	*
21483.....	7.06	B3	+ .11	.30	2.5	300	*
22298.....	7.8	B5e	+ .06	.23			
23675.....	6.76	B1	+ .08	.29	5.5	1100	
23800.....	6.87	B1	+ .01	.22	3.5	600	
24432.....	7.02	B4	+ .09	.27	-5.0	1100	
24534.....	var.	Bo:e	+0.04	+0.26			*

TABLE 4—Continued

HD	Vis. Mag.	Spec. Type	Obs. Color	Color Excess	Abs. Mag.	Distance	Re- marks
25090.....	7.28	B1	+0.04	+0.25	-4.5	1000	
25443.....	6.75	B1	+ .02	.23	5.0	1100	
25638-9.....	{7.0	Bo inc.}	+ .08	{.30}			*
		Bi inc.}		.29}			
25914.....	8.1	B9	+ .13	.25	5.8	2700	
27795.....	7.16	B3	+ .02	.21	3.0	550	
31327.....	6.18	B2	+ .08	.28	3.5	350	
32481.....	8.1	B3	+ .04	.23	3.5	1000	
33203.....	6.17	B2	+ .21	.41	3.5	300	*
34921.....	7.39	Be	- .01	.19			
35395.....	6.83	O9+	+ .02	.25			
35619.....	8.5	O6	- .02	.21			
35633.....	7.9	O7	- .01	.22			
36483.....	8.4	O7	+ .04	.27			
39970.....	6.02	A2	+ .06	.11	5.5	1400	
41398.....	7.45	B1	- .02	.19	6.0	2600	
42379.....	7.6	O9		.23			
43384.....	6.26	B2	+ .01	.21	5.0	900	
43818.....	7.03	Bo		.22	5.0	1300	
46485.....	8.4	B5: inc.		.17			
50820.....	6.25	Bp	+ .15	.35			
51480.....	6.97	B5q	+ .02	.19			
53367.....	7.01	O8e	+ .06	.29			
60308.....	8.30	B4	+ .05	.23	5.0	2200	
147889.....	8.0	B3:	+ .31	.50	2.7	300	
150475.....	8.6	O7	+ .01	.24			
151397.....	9.5	Bo	+ .01	.23	3.5	1900	
154090.....	4.87	Bo+ea	- .01	.21	5.3	550	
156134.....	8.3	Bo	+ .12	.34	5.6	2000	
156154.....	8.3	O8	+ .11	.34			
156201.....	7.77	Bo	+ .16	.38	5.3	1200	
158705.....	7.81	B1	+ .22	.43	5.2	1000	
160529.....	6.68	A2ea	+ .47	.52	5.5	500	
161056.....	6.20	B1+	+ .05	.26	3.5	400	
161103.....	8.5	B2e	+ .04	.24			*
161306.....	8.31	B3:e	+ .13	.32			*
162168.....	8.6	Bo+	+ .15	.37	5.0	1600	
162717.....	9.3	B3	+ .17	.36	4.0	1400	
162718.....	8.7	B3:e	+ .20	.39			*
163777.....	9.5:	B1	+ .07	.28	5.2	3500	
164103.....	8.04	O8	+ .07	.30			
164865.....	7.9	B8	+ .31	.44	5.6	1200	
165049.....	8.07	B1+	+ .09	.30	4.0	1000	
165285.....	8.73	Bo:e	+ .02	.24			*
165319.....	8.2	Bo	+ .11	.33	4.5	1200	
165517.....	8.55	Bo:e	+ .12	.34			
165655.....	8.3	B1 inc.	+ .01	.22			
165892.....	9.2	B2	+ .10	.30	3.0	1000	
165998.....	8.5	B8	+ .24	.37	4.0	950	
166418.....	8.2	Bo	+ .07	.29	4.5	1400	
166787.....	8.4	Bo	+0.10	+0.32	-5.5	2200	

TABLE 4—Continued

HD	Vis. Mag.	Spec. Type	Obs. Color	Color Excess	Abs. Mag.	Distance	Re- marks
166965.....	8.8	B2	+0.03	+0.23	-2.5	850	
167330.....	8.4	B0	+ .13	.35	5.5	2000	
MWC287.....	8.7	Be	- .02	.18			
167451.....	8.7	B1	+ .17	.38	5.0	1600	
167543.....	8.8	B2	+ .04	.24	4.5	2100	
167838.....	6.64	B6	+ .08	.24	5.6	1300	
167971.....	7.34	B0 inc.	+ .22	.44			*
168183.....	8.2	B0	.00	.22	4.0	1400	*
168352.....	8.9	B2+	+ .02	.22	3.5	1500	
168552.....	8.3	B1+	+ .04	.25	4.0	1300	
168571.....	8.0	B1	+ .13	.34	4.5	1100	
169034.....	8.6	B2	+ .45	.65	5.2	700	
169454.....	6.84	B1e	+ .29	.50	6.0	750	*
169754.....	9.0	B2	+ .36	.56	5.0	1000	
170714.....	7.31	B3	+ .04	.23	3.5	700	
170740.....	5.80	B4	+ .03	.21	3.5	350	*
170938.....	8.1	B1	+ .28	.49	5.7	1200	*
171012.....	6.98	Boea	+ .06	.28	5.0	1000	
173438.....	8.6	Boea	+ .20	.42	5.0	1400	
174571.....	9.1	B2e	+ .08	.28			
175514.....	9.0	O6	+ .08	.31			
177812.....	8.9	B1+	+ .14	.35	5.4	2300	
178129.....	7.8	B3	+ .07	.26	5.0	1600	
178849.....	6.63	B3	(+ .34)	(.53)	2.5	(50)	*
183143.....	6.93	B8+ea	+ .38	.51	6.0	750	
E231616.....	10.3	B1	+ .13	.34	3.0	1500	*
185859.....	6.44	Bo+	+ .04	.26	5.2	900	
E227415.....	9.9	B0	+ .08	.30	2.5	1100	
E227460.....	9.9	B1	+ .28	.49	3.5	1000	
190603.....	5.69	B1eβ	+ .13	.34	5.8	650	
E227611.....	8.7	Be	+ .01	.21			
190919.....	7.30	B1	.00	.21	4.0	900	
E227836.....	9.6	B5ea	+ .02	.19	5.5	5700	
E228041.....	9.2	Be	+ .03	.23			
192422.....	7.10	B0	+ .05	.27	5.2	1200	
E228548.....	10.3	B1e	+ .19	.40			
193183.....	7.12	B2	+ .08	.28	4.5	850	
E228841.....	9.1	O6	+ .10	.33			
193443.....	7.4	O9:	+ .03	.26			
194279.....	7.05	B2	+ .33	.53	5.8	650	
E229221.....	9.6	Boe	+ .28	.50			
194839.....	7.45	Boea	+ .34	.56	5.5	650	
195592.....	7.15	Boea	+ .30	.52	5.7	700	
197460.....	8.2	Bo+	+ .01	.23	4.0	1300	
197770.....	6.36	B2	+ .03	.23	4.0	550	
198895.....	8.26	B3e	+ .14	.33			
199216.....	7.13	B1	+ .11	.32	4.5	750	
200775.....	7.20	B1e	+ .07	.28			
200857.....	7.16	B2	+ .16	.36	-4.5	650	
203374.....	6.64	Bo:e	+0.01	+0.23			

TABLE 4—*Continued*

HD	Vis. Mag.	Spec. Type	Obs. Color	Color Excess	Abs. Mag.	Distance	Re- marks
203938.....	7.10	B1	+0.13	+0.34	-4.0	550	
204116.....	7.96	B1	+ .09	.30	3.0	600	
204827.....	8.3	B4	+ .15	.33	3.5	800	
205196.....	7.36	B0	+ .15	.37	5.2	1000	
207260.....	4.46	A1	+ .16	.23	5.5	450	
207329.....	7.45	B1e	+ .03	.24	.....	.....	
207757.....	7.5	Bep	+ .06	.26	.....	.....	*
207793.....	6.56	B1	+ .06	.27	5.0	850	
207872.....	8.2	B0+	+ .04	.26	3.0	750	
208218.....	6.76	B1+	+ .01	.22	4.0	700	
209744.....	6.74	B2	+ .01	.21	3.5	550	
210352B.....	9.8	B4	+ .10	.28	1.0	600	
212455.....	8.0	B4	+ .09	.27	4.5	1300	
213087.....	5.66	B0	+ .01	.23	5.2	750	
216014.....	6.83	B0 inc.	+ .05	.27	.....	.....	
216411.....	7.16	B1ea	+ .15	.36	6.0	1300	*
216711.....	9.2	B4	+ .16	.34	2.0	600	
216898.....	8.3	O8+	+ .09	.32	.....	.....	
217035.....	7.76	B0	+ .05	.27	3.0	850	*
217297.....	7.36	B2	+ .01	.21	4.0	950	
218342.....	7.46	B1	+ .10	.31	5.0	1100	
223385.....	5.61	Aoea	+ .24	.34	5.5	550	
223960.....	6.98	Aoea	+ .21	.31	5.5	1200	
223987.....	7.56	B0	+ .08	.30	4.5	1000	
224055.....	7.16	B5ea	+ .20	.37	6.0	1300	
224424.....	8.4	B1ea	+ .21	.42	3.5	600	
225094.....	6.26	O7+ea	+ .02	.25	.....	.....	
225146.....	8.6	B0	-0.02	+0.20	-4.5	2200	

NOTES TO TABLE 4

7902	K line appears strong	164865	In M 8, nebula
14956	Like HD 169454	165285	D ₃ in emission
15570	He II 4686 in emission	167971	In NGC 6604
19243	Strong feature near 4120. Diffuse fea- ture near 4215. 4009 (?) diffuse, 4026 and 4471 fairly sharp	168183	In M 16
		169454	Strong O II, especially lines near 4345 and 4419
21389	Appears in small nebula on <i>Ross Atlas</i>	170740	In IC 9287
21448	ADS 2559, Σ 391. 7.3 mag., 8.0 mag. Combined spectrum	170938	Like 169454
21483	In Barnard 204	178849	Companion A0. Star appears of normal color on plate taken by Tikhov meth- od for obtaining color. ADS 12093, Σ 2470. 6.63 mag. and 8.0 mag.
24534	X Persei	E231616	Appears nebulous on <i>Ross Atlas</i>
33203	ADS 3734, Σ 664. 6.7 mag., 7.0 mag. Combined spectrum	207757	AG Pegasi. Color perhaps due to red companion discovered by Swings and Struve
25638-9	ADS 2984, Σ 485, and Σ 484, in NGC 1502. The preceding star is listed first in table	216411	Like 169454
161103	Double star. Brighter component	217035	ADS 16394, Σ 2961, 8.0 mag., 8.0 mag. Type for combined spectrum
161306	D ₃ in emission?		
162718	H lines have absorption cores. 3965 and 3888 strong		

II. DISCUSSION

The strong galactic concentration of the reddened B stars which was pointed out by Stebbins and Huffer is exhibited in Figure 1. The reddened Be stars are evidently less closely concentrated to the galactic plane than the normal reddened B stars; in fact, their dispersion about the galactic plane is 8.3 ± 1.1 (mean error); that of the normal B's is 4.0 ± 0.2 . If even a fraction of the Be stars are intrinsically reddened, then the reddened Be stars will not show the extreme galactic concentration of the normal reddened B stars, since this effect is at least partly due to the absorbing layer. This cannot be the effect of weaker galactic concentration in the Be's than in the normal B's, for the mean galactic latitude of all emission B's in the catalogue of Stebbins, Huffer, and Whitford is 11.6 ± 0.6 ; that of the nonemission B's is 13.9 ± 0.3 . If, however, the dispersion in the luminosities of the normal B's is, as seems probable, much larger than that of the Be's, then it is likely that the reddened B's have a higher average absolute magnitude than the reddened Be's, even though the nonreddened B's have the same or lower. This would account for the effect. On the other hand, there is other evidence that at least some Be stars,⁹ such as γ Cassiopeiae, Pleione,¹⁰ and P Cygni,¹¹ are reddened by intrinsic causes. For this reason the Be stars (excepting the *ea* stars) and the incipient Be stars are not considered reliable indicators of space absorption and are excluded in the remainder of the discussion.

The distribution of the reddened B stars exhibits a second peculiarity, namely, the avoidance of the regions from $l = 345^\circ$ to $l = 40^\circ$, north of the galactic plane; from $l = 115^\circ$ to $l = 150^\circ$, on both sides; and, less definitely, from 50° to 60° and from 80° to 90° , north of the galactic plane. The

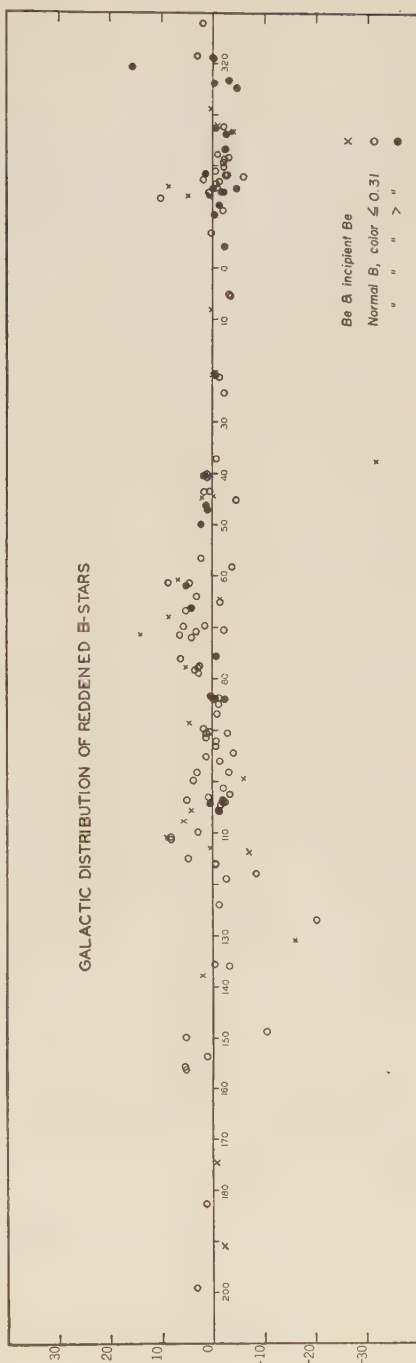


FIG. 1.—The galactic distribution of the reddened B stars

⁹ E. G. Williams, *Ap. J.*, **79**, 299, 1934.

¹⁰ E. G. Williams, *Observatory*, **62**, 301, 1939.

¹¹ F. Sherman and W. W. Morgan, *Ap. J.*, **89**, 509, 1939.

accompanying plates show that each of the regions of avoidance is a dark region of the Milky Way. The fidelity of the Ross-Calvert mosaic to the general features of the Milky Way, as well as its finer detail, can be tested by a comparison with A. Pannekoek's photometric studies of the northern¹² and southern¹³ Milky Way. The agreement of the major features is satisfactory.

The distribution in depth.—In Figure 2, the color excesses of the stars of Table 7 are plotted against their distances. The double cluster in Perseus is plotted at the previously derived distance of 1400 parsecs and with the colors of the stars of Table 4 which are members of the cluster. The vacant spaces at the bottom and upper right of the figure are due to selection. The former is due to the choice of stars to which Stebbins, Huffer, and Whitford assign a color excess of $+0.20$ or more; and the second to the impossibility of observing distant stars of very heavy reddening, because of their faintness.

The solid line in Figure 2 represents Stebbins, Huffer, and Whitford's average coefficient c of selective absorption, 0.12 mag/kpc, which is in rough agreement with other determinations of the average absorption. Obviously, we cannot account for the reddening of the majority of the stars of this paper by an average coefficient of selective absorption. There is no contradiction here with the results of the photoelectric observers, since stars of low reddening are excluded from the present paper and since they excluded certain heavily reddened stars. The heavily reddened B stars cannot be brought into line with the average coefficient of selective absorption even if they are assigned absolute magnitudes as high as -6.5 . Since Hubble has shown¹⁴ that this is of the order of the mean photographic luminosity of the brightest stars in a galaxy, a further great increase in our estimates is improbable.

Stars giving a large coefficient of absorption.—Two of the three causes of abnormally large reddening which were suggested at the beginning of the discussion have been considered, namely, the stars of very high luminosity and those with intrinsic reddening. To test the third possibility, that they are connected with regions of unusually great absorption, the dotted line has been drawn in Figure 2, representing a coefficient of selective absorption of 0.5 mag/kpc. The stars lying to the left of this line are undoubtedly unusually heavily reddened; the luminosity of any one of them would have to be increased by 3.1 mag. to bring it into agreement with the mean coefficient of selective absorption. These stars are plotted on the Ross-Calvert mosaic in Plate XVIII. It is evident upon inspection that most of them are connected with dark masses, notably the rift nebula, the dark nebulosity around the North America nebula, and the dark nebula in Auriga. HD 21483, which is not included on the mosaic, lies at the end of the dark nebula B 204. The association of the most heavily reddened B stars with the edges of dark masses has been pointed out by Stebbins, Huffer, and Whitford.¹⁵

Stars giving a normal coefficient of absorption.—On Plate XIX are plotted the stars lying below and to the right of the broken line in Figure 2. For these stars the computed absorption coefficient is not greater than 0.15 mag/kpc, and hence of the order of the average coefficient of selective absorption. These stars of normal reddening are distributed quite differently from the stars of very high reddening. There are several of them in the bright region from $l = 335^\circ$ to $l = 342^\circ$, where there is none of the others; and there is none beyond $l = 342^\circ$, although several of the first group are present. Another fraction of this group is in the bright part of Cassiopeia following $l = 80^\circ$, and in the region of the double cluster in Perseus. Comparison with the abnormally reddened stars indicates a marked decrease in the absorption near $l = 80^\circ$.

Analysis by regions.—The distances given in Table 4 can be used to determine the distances and to measure the absorption of the obscuring matter in each of the principal divisions of the northern Milky Way. In general, these results follow a certain pattern.

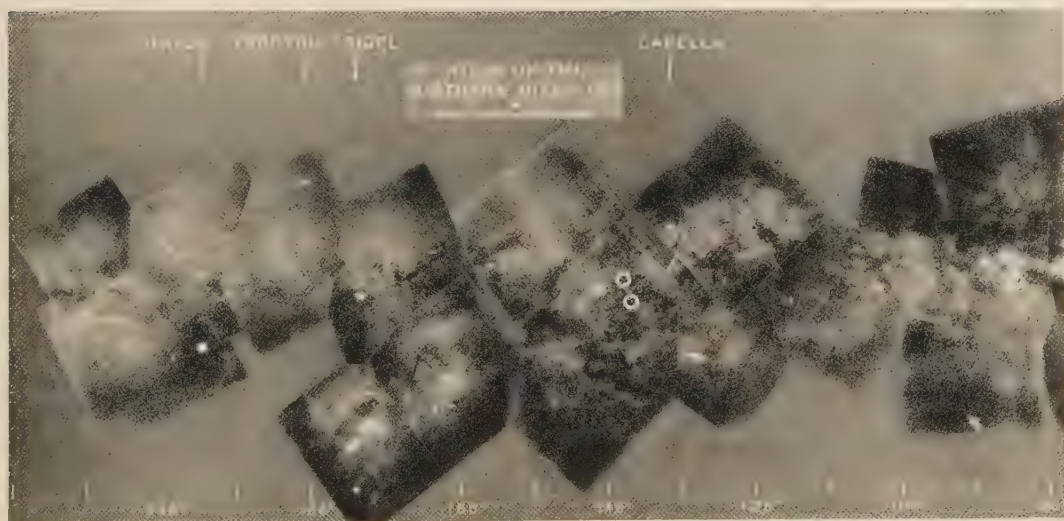
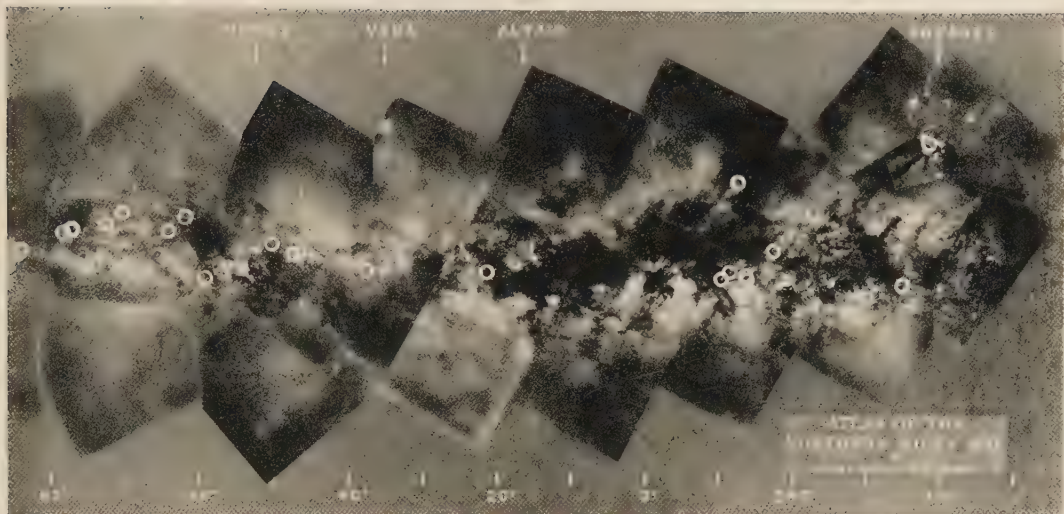
¹² *Leiden Ann.*, **11**, Part III, 1920.

¹⁴ *Ap. J.*, **84**, 164, 1936.

¹³ *Bosscha Ann.*, **2**, Part I, 1932.

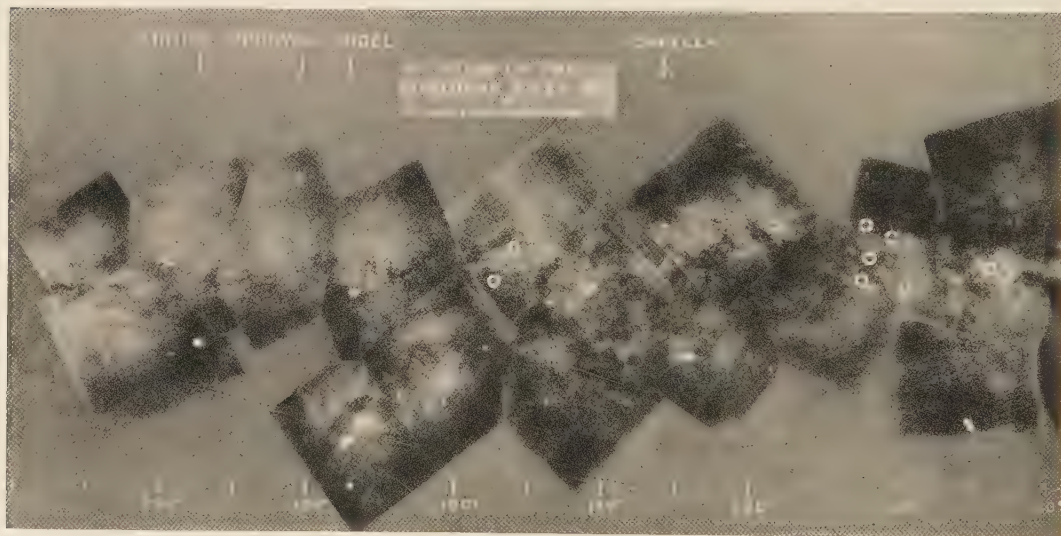
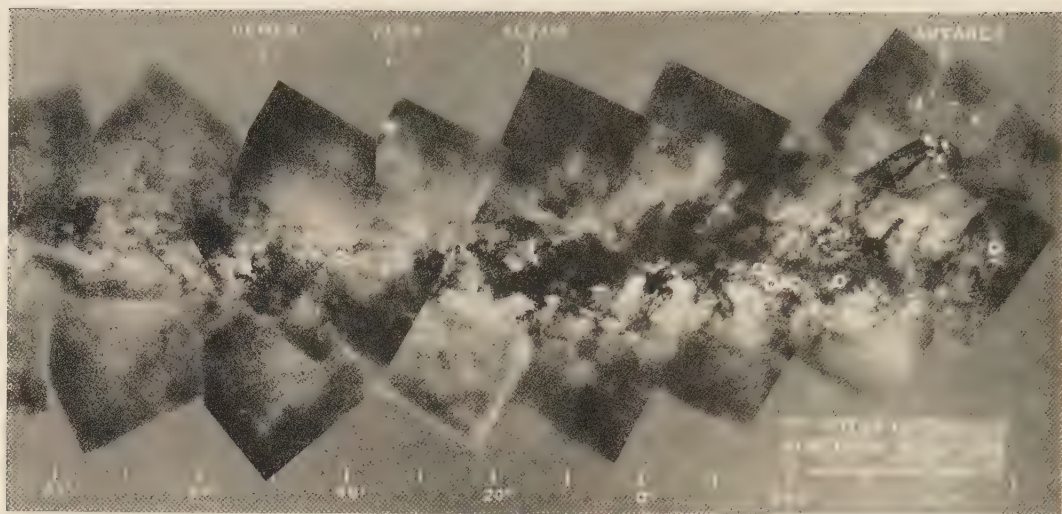
¹⁵ *Op. cit.*, **90**, 223, 1939.

PLATE XVIII



STARS HAVING AN AVERAGE COEFFICIENT OF SELECTIVE ABSORPTION NOT LESS THAN 0.50 MAG/KPC
Plotted on a mosaic made from the *Ross Atlas* by Miss Mary R. Calvert

PLATE XIX



STARS HAVING AN AVERAGE COEFFICIENT OF SELECTIVE ABSORPTION NOT GREATER THAN 0.15 MAG/KPC
Plotted on a mosaic made from the *Ross Atlas* by Miss Mary R. Calvert

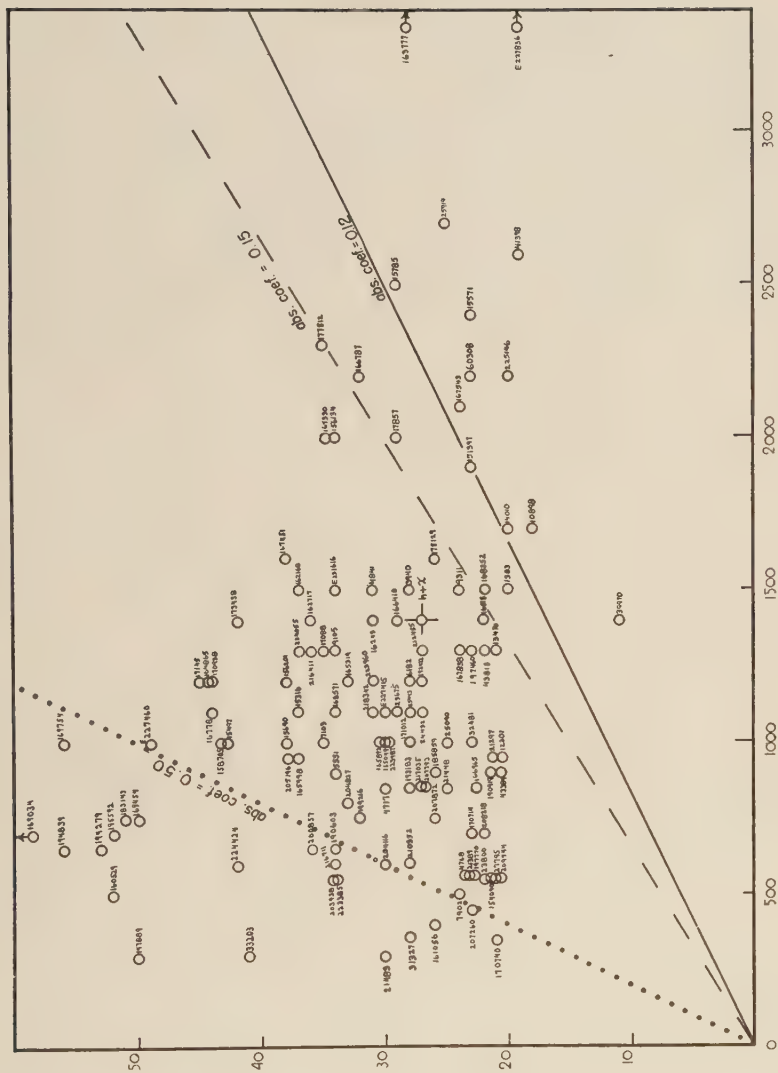


FIG. 2.—The color excesses and distances of the reddened B stars

Two series of obscuring nebulosities seem to bound a clear lane in which the sun lies. One series lies on the side toward the galactic center and is seen as the rift, extending from near-by matter at $l = 340^\circ$ to distant dark nebulae in Cygnus. The outer series begins in the dark matter in Cygnus and extends toward the sun through the dark matter in Cepheus; it is at its nearest in Auriga and Perseus and is more distant in the portion of Orion which lies near the galactic plane. Each of these series has holes through which much more distant stars are visible.

The series on the side toward the galactic center begins with the dark mass near θ Ophiuchi, for which, from HD 160529, a distance of less than 500 parsecs and an absorption of 3.6 mag. in the outer parts is found. Between this dark nebula and the southern end of the rift (i.e., from $l = 332^\circ$ to $l = 342^\circ$) there is a gap in the series. Nine stars in this region at distances not less than 1000 parsecs are listed in Table 5.

The next region is the southern end of the rift. For this cloud we have a distance of 350 parsecs from HD 170740, which is actually in the dark nebula and illuminates it. HD 161056 gives an accordant value of less than 400 parsecs. The nebulosity near ρ Ophiuchi, which is probably connected with this, has, from HD 147889, which illuminates it, a distance of 300 parsecs.

TABLE 5
DISTANT STARS BETWEEN LONGITUDES 332° AND 342°

HD	Absorption (Mag.)	Distance (Parsecs)	HD	Absorption (Mag.)	Distance (Parsecs)
162717.....	2.5	1400	166418.....	2.0	1400
163777.....	2.0	3500	166787.....	2.2	2200
164865.....	3.1	1200	168352.....	1.5	1500
165049.....	2.1	1000	168571.....	2.4	1100
165892.....	2.1	1000			

These values are considerably higher than other determinations. From star counts Greenstein¹⁶ finds a distance of 125 parsecs. For the nebulosity near ρ Ophiuchi, Struve and Greenstein¹⁷ find a distance of 100 parsecs. This discrepancy results from the use of a value of 7 for the ratio of color excess to total visual absorption in this paper, compared with 8 in theirs; and a value of -2.7 for the luminosity of the main-sequence B3 star HD 147889, compared with their value of -1.0 .

The values found for the absorption in this nebula go up as high as 4.5 mag. for HD 169034. The average value given by Greenstein is 0.9 mag. An average value cannot be found spectroscopically unless account is taken of the nonreddened stars; hence, there is no real contradiction here.

Along the remainder of the rift, as far as $l = 30^\circ$, there are no more near-by reddened B stars of the present list—a fact which suggests that the matter is at greater distances. The nearest reddened B star is HD 183143 at a distance of 750 parsecs at $l = 25^\circ$. It has suffered an absorption of 3.6 mag. There is a strong suggestion, from the general appearance of the *Ross Atlas*, that the number of stars between us and the dark matter is greater at this northern part of the rift than at the southern end.

The region of the southern part of the Cygnus cloud, together with a dark cloud belonging to the rift at $l = 35^\circ$, contains no reddened B stars of this program. At the northern end there are regions of unusual transparency, in which are 2 reddened main-sequence B stars at the tenth magnitude (E227415 and E227460 at distances of 1100 and 1000 parsecs, respectively). This region ends in a dense dark nebula at the northern end

¹⁶ *Harvard Ann.*, 105, 359, 1936.

¹⁷ *Ap. J.*, 90, 625, 1939.

of the cloud, surrounding the North America nebula, which is indicated, by the present material, to be at a distance not greater than 650 parsecs. It forms the beginning of the outer series of obscuring clouds. The absorption is very great; several reddened stars at the edges have suffered more than 3.5 mag. absorption, and they cease altogether in the middle of the dark cloud.

In the region from $l = 55^\circ$ to $l = 80^\circ$ there are 20 stars of this paper with known distances. The least distance is 450 parsecs for HD 207260, and only 3 stars (HD 212455, 216411, and 218342) are at distances greater than 1000 parsecs. This narrow range in distance is not merely observational, since there is a range in apparent magnitude from 4.5 mag. to 9.8 mag. The absorption appears to set in at 550 parsecs, since there are several stars at this distance and only one at a smaller distance. It attains values up to 2.5 mag. In Table 6 the individual absorptions and distances are given.

In the Cassiopeia-Perseus region, which is here taken as extending from $l = 80^\circ$ to $l = 110^\circ$ and which includes the following portion of Cassiopeia, together with a small portion of the preceding end of Perseus, including the double cluster, there are 35 stars

TABLE 6
STARS IN THE CEPHEUS-CASSIOPEIA REGION

HD	Absorption	Distance	HD	Absorption	Distance
197770.....	1.6	550	208218.....	1.5	700
199216.....	2.2	750	209744.....	1.5	550
200857.....	2.5	650	210352B.....	2.0	600
203938.....	2.4	550	212455.....	1.9	1300
204116.....	2.1	600	213087.....	1.6	700
204827.....	2.3	800	216411.....	2.5	1300
205196.....	2.6	1000	216711.....	2.4	600
207260.....	1.6	450	217035.....	1.9	850
207793.....	1.9	850	217297.....	1.5	950
207872.....	1.8	750	218342.....	2.2	1100

with known distances, counting the double cluster as 1 star. Of these, only 6 stars have distances less than 1000 parsecs. Four stars (HD 225146, 15571, 15785, and 17857) are at distances of 2000 parsecs or more. For such a region it is difficult to assign a distance to the absorbing material; it is evident that there is little dark nebulae dense enough to produce reddening greater than 0.20 mag. until distances of the order of 1000 parsecs are reached. It is evidently a hole in the outer series of dark nebulae.

Near longitude 110° the outer series of dark nebulae continues. A dark region extends through the following part of Perseus and into Auriga, as far as $l = 140^\circ$. At the preceding end of the mass is the star HD 21389, which appears nebulous on the *Ross Atlas*. This determines the distances of the dark matter near $l = 110^\circ$ as 550 parsecs. In the region of Auriga, at $l = 135^\circ$, or nearly opposite the nebulae in Ophiuchus, we find HD 31327, 33203, and 21483—all at distances of the order of 300 parsecs. Absorptions in this region, which is probably connected with the Taurus nebulae, range up to 2.9 mag. for HD 33203.

Here, as in the case of the Ophiuchus dark nebula, there is a considerable divergence between the distances from star counts and those from the reddened B stars. Greenstein¹⁸ gives a distance of 145 parsecs for the Taurus nebula. The 3 stars found here beyond the Taurus-Auriga portion of the nebula are all main-sequence B stars; hence the matter depends on Williams' absolute magnitudes of such stars. The largest discrepancy, for HD 21389, in the Perseus portion of the nebula, follows directly from the

¹⁸ *Loc. cit.*

absolute magnitude of -5.5 assumed here for cA stars. The divergence from the results of the star counts may perhaps be due in part to the extension of the Taurus nebulosity in the line of sight. The Taurus nebula has an enormous extension on the sky; it is probably connected with the dark masses in southern Orion on one side and in Perseus on the other; hence it is not improbable that its radial extension is also very great.

From 4 stars (HD 39970, 41398, 43384, and 43818) in northern Orion and the southern part of Gemini we find for the obscuring matter in this region a maximum distance of 900 parsecs and absorptions as high as 1.5 mag. From this region onward through Monoceros the Milky Way appears to be extremely transparent. Even if allowance is made for the incompleteness of the photoelectric colors at this low declination, the small number of the heavily reddened stars is striking.

Comparison with other determinations.—The results of the discussion of the absorbing matter of the Milky Way are summarized in Table 7. For comparison the distances and average absorptions determined from star counts are taken from Greenstein's summary.¹⁹

TABLE 7
DISTANCES AND ABSORPTIONS OF THE DARK NEBULAE

GALACTIC LONGITUDE	REGION	SPECTROSCOPIC DETERMINATIONS		DETERMINATION FROM STAR COUNTS	
		Absorption (m_{vis})	Distance (Parsecs)	Absorption (m_{pg})	Distance (Parsecs)
340°–350°	Ophiuchus	3.5	300	0.9	125
25°	Cyg–Sge	3.6	<750	.....	.....
45°–55°	Cygnus	3.9	<650	1.5	700
55°–80°	Cep–Cas	2.5	550	0.7	500
110°–140°	Per, Aur, Tau	2.9	<300	1.1	145
150°	Ori–Mon	1.5	<900	.....	.....

The dark matter in Orion and Monoceros near $l = 150^\circ$ is not far from the dark nebula near S Monocerotis. Wolf²⁰ found for this dark nebula a distance of 800 parsecs and an absorption of 2 mag. photographic. These values are quoted by Bok.²¹

The agreement between the distances determined spectroscopically and those from star counts is fair for the dark nebulae in Orion, Cepheus–Cassiopeia, and Cygnus; it is poor for the nearest nebulosities, in Ophiuchus and Taurus, as has been remarked. Because of the small number of stars used in these determinations of distance, they cannot be regarded as of equal weight with those from other sources. They serve principally to check the hypothesis that the dark masses are responsible for the heavily reddened B stars. The absorptions found in this paper are not comparable with the average absorptions found from star counts. These values are always maximum observed absorptions. Without data on the distances of the less reddened stars, average absorptions cannot be found. Moreover, the complete absence of reddened B stars from the densest parts of the dark regions in Cygnus, Sagitta, Serpens, and Ophiuchus suggests that the absorptions there are so high and set in so suddenly as to be out of reach by the present methods.

The recession of the dark matter of the rift as one proceeds from Ophiuchus along the Milky Way toward the southern part of Cygnus is suggestive. If one accepts a distance of 300 parsecs at $l = 340^\circ$ and one of 750 parsecs at $l = 25^\circ$, this mass is found to lie at

¹⁹ *Loc. cit.*

²⁰ *Seeliger Festschrift*, p. 312, Berlin: Julius Springer, 1924.

²¹ *The Distribution of the Stars in Space*, p. 81, Chicago: University of Chicago Press, 1937.

an angle of between 75° and 80° to a radius from the center. It would thus bound, on the side toward the galactic center, a clear region, surrounding the sun and extending toward the Cygnus cloud. The boundary on the side away from the galactic center is formed by the Cygnus, Cepheus, Taurus-Auriga nebulosities, and the dark nebula near S Monocerotis. Such a clear space was suggested by Stebbins and Huffer in their discussion of the reddened B stars, except that they regarded it as directed toward $l = 10^\circ$. In this direction they had found very few reddened B stars. But if one accepts the interpretation of the present paper, that the absence of reddened B stars in the blacker parts of the rift is a consequence of their great absorption, then it is necessary to shift the direction of the clear lane northward toward that indicated by the present paper. The independent evidence from the blue B stars²² would by itself suggest such a direction for this clear space.

It is a pleasure to express my gratitude to Dr. Otto Struve and Dr. W. W. Morgan for their help and criticism in carrying out this investigation, and to Mr. F. R. Sullivan, who helped in the observations.

YERKES OBSERVATORY
June 1941

²² Cf. the diagram by Stebbins and Huffer, *op. cit.*, p. 249.

